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On the close optical companion of V1494 Aql: problems with light curve modelling[⋆]

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Abstract. New observations of the eclipsing nova V1494 Aql were analysed in order to estimate the effect of the optical companion located $1\overset{''}{.}4$ southwest. R and I-band images (stellar $FWHM \approx 1\overset{''}{.}2 - 1\overset{''}{.}4$) taken close to the primary minimum were used to determine relative magnitude differences between the nova and the companion, which were found to be $\Delta R \approx 0\overset{m}{.}20$ and $\Delta I \approx 0\overset{m}{.}52$ (in the sense nova *minus* companion). After correcting R-band time-series observations for the secondary light, the eclipse depth has been found to be almost twice as deep. Before modelling any late eclipsing light curve that is available in the literature, the data must be corrected for the light of the companion.

Key words. stars: novae – stars: individual: V1494 Aql

1. Introduction

V1494 Aql (=Nova Aql 1999/2) has been one of the brightest nova outbursts in the last decade. Shortly after the discovery in December, 1999 (Pereira et al. 1999), it peaked at $m_{vis} = 4$ mag, which has been followed by rapid dimming ($t_3 = 16$ d, Kiss & Thomson 2000). The light curve showed a classical transition phase with quasi-periodic oscillations (see an updated light curve in Kato et al. 2003). Optical spectroscopy (Kiss & Thomson 2000, Anupama et al. 2001, Arkhipova et al. 2002, Iijama & Esenoglu 2003) showed that the nova belonged to the "Fe II" class of Williams (1992) with early expansion velocities up to 2000 km s^{-1}. Spectroscopy in the transition phase suggested the presence of high velocity jets, while the MMRD absolute magnitude (Kiss & Thomson 2000) has been combined with spectroscopic reddening determination which placed the star 1.6±0.2 kpc of the Sun (Iijama & Esenoglu 2003). Early X-ray observations were reported by Drake et al. (2003) revealing short-period (2523 s) oscillations that were interpreted as pulsations of the white dwarf in the nova. Spectropolarimetric evidence of an asymmetric outburst was presented by Kawabata et al. (2001).

The photometric history is rich in observations. Kato et al. (2003) gave an excellent review of the published works, here we just briefly mention the main results. After the discovery of short-period modulations of the light curve (Novak et al. 2000), Retter et al. (2000) pointed out the double-wave nature of the

modulation with a peak-to-peak amplitude of $0\overset{m}{.}07$, 8 months after the outburst. Bos et al (2001) observed a strong amplitude increase of the modulation and suggested the eclipsing nature of the system. Barsukova & Goranskii (2003) refined the orbital period, giving $P_{orb} = 0.1346141(5)$ d. Pavlenko et al. (2003) made a multicolour study of the star concluding that the light curve shape might be explained by a self eclipsing accretion column in the magnetic variable accompanied with partial eclipses of the accretion region by the secondary component.

We have been following the star since the discovery, mostly monitoring it spectroscopically (Kiss & Thomson 2000, Kiss et al. in preparation). Here we report on new imaging and spectroscopy carried out in 2003, which revealed the presence of a close optical companion (it has already been reported by Barsukova & Goranskii 2003, however, we were not aware of it before making the observations). Interestingly, none of the recent studies tried to correct for the photometric effects of the companion. In this paper we would like to point out the necessity of such a correction.

2. Observations and data reductions

We discuss three different datasets. In chronological order, they were taken as follows. On May 10, 2003, between HJD=2 452 770.148–2 452 770.317, four hours of service observations were carried out using the 3.9m Anglo-Australian Telescope (AAT) equipped with the RGO spectrograph. We obtained 41 medium-resolution spectra (exposure time 300 s) covering 5800–7300 Å, with typical S/N ratios of 50 ($\lambda/\Delta\lambda = 6000$). One flux standard and one smooth-spectrum standard star were also observed. The seeing on that night was about
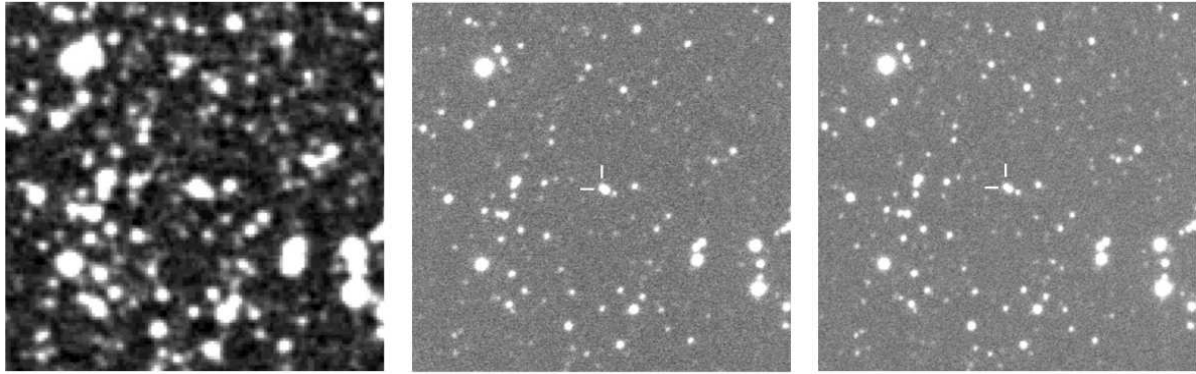

Fig. 1. $120'' \times 120''$ fields centered on V1494 Aql. Left to right: POSS2 red, *R*-band image at HJD=2 452 930.9568 (stellar *FWHM* = $1''.4$), *I*-band image at HJD=2 452 930.9526 (*FWHM* = $1''.2$). Dashes point to the nova, identified through the eclipses. North is up, east is to the left.

$1''.3$, as judged from the width of the standard spectra. The position angle of the 2-arcsec wide slit was constant at $200°$.

Then we made time-series *R*-band observations with the 1.0m telescope of the Australian National University in Siding Spring on three consecutive nights in August, 2003 (6-8th), with a total time span of ~12 h. The detector was the middle 1k×1k subframe of one of the eight 2k×4k chips of the Wide Field Imager, giving $6'.5 \times 6'.5$ field of view (this corresponds to $0''.38$/pixel image scale). The exposure time was 180 s. Since V1494 Aql was a secondary target for bright and medium to bad seeing nights (the primary program addressed globular clusters), these time-series data were obtained under 2.5 to 5 arcsec seeings.

Finally, the last dataset consists of eight CCD images (4 in *R* and 4 in *I*) taken on Oct. 18, 2003. The instrument was the same as in August, 2003. The seeing varied between $1''.2$–$1''.4$, which has been the best one experienced in a three-weeks long run. The exposure time was only 30 s in order to get as sharp images as possible. We noticed the optical companion of V1494 Aql and that has initiated a careful re-check of the literature and previous data.

All observations were reduced with IRAF[1] in a standard fashion. Spectroscopic reductions included bias, flat and sky background corrections. Aperture extraction and wavelength calibrations were done with the task *doslit* utilizing CuAr spectral lamp exposures taken before and after every ten stellar exposures. The flux calibration used a spectrum of LTT 7379, a G0-type spectroscopic standard. Time-series direct images were corrected with bias and sky-flat frames, while instrumental *R*-band magnitudes were calculated with simple aperture photometry (the diameter of the aperture was set to $6''.5$) in respect to comparison stars located within $1'.0$. Following Barsukova & Goranskii 2003, the main comparison was GSC 0473–4227. Typical photometric accuracy was $\pm0^{m}.01 - 0^{m}.02$.

3. Discussion

3.1. Astrometry

The original purpose of making sharp images on October 18, 2003 was checking the presence or absence of a resolvable nova shell. The predicted angular radius of the shell 3.8 years after the outburst is $0''.94$ (following Kiss & Thomson 2000 and adopting the distance revised by Iijama & Esenoglu 2003). Instead of a shell, we found two closely separated stars within $\pm1''$. In Fig. 1 we show our best CCD frames compared to the POSS2 red image (this is the sharpest POSS2 image). It is quite obvious that the 8-shaped profile is caused by two stars close to the limit of resolution. The POSS2 image has too low resolution and is too crowded to recognize this. None of the available POSS, POSS2 and 2MASS images of the field shows the nova and its companion resolved, so that our first conclusion is that we do not have any direct information on the progenitor.

The next step was the identification of the eclipsing component. For this, we used our time-series observations taken 2 months earlier. Even the best images were made under $2''.5$ seeing, which disabled earlier recognition of the pair. Image differences, however, showed that the eclipsing variable is the eastern component, as has been also concluded by Barsukova & Goranskii (2003).

Although the chance of having a nova and an eclipsing binary within $2''$ seems to be very close to zero (the colours reported by Barsukova & Goranskii 2003 did not support it either), we made an astrometric solution of the best *I*-band image and compared the coordinates to the published values. We chose 21 non-saturated stars within $\pm1'$ of the nova and took their J2000.0 coordinates from the GSC2.2 catalog. Pixel coordinates were determined by psf-fitting (with the *daophot* package in IRAF). The residuals of the solution were $\pm0''.2$, which we adopted as the astrometric uncertainty. The resulting coordinates are shown in Table 1. We plot them together with the coordinates of the nova and assumed progenitor (Pereira et al. 1999) in Fig. 2. According to this, the separation and the position angle of the companion are $1''.4$ and $230°$, respectively.

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[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
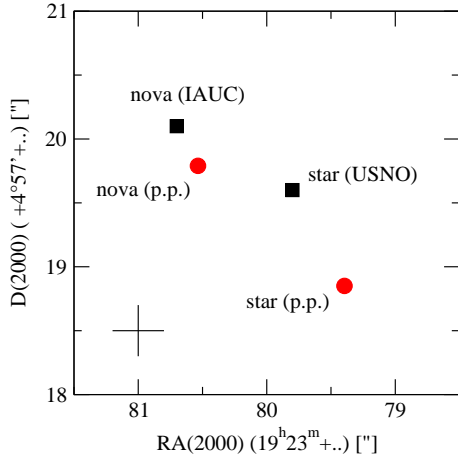
Fig. 2. A comparison of the new astrometric solution and published coordinates of the nova and the suspected progenitor (Pereira et al. 1999). The cross in the left corner shows the uncertainty.

Table 1. Astrometry and photometry of the nova and the companion.

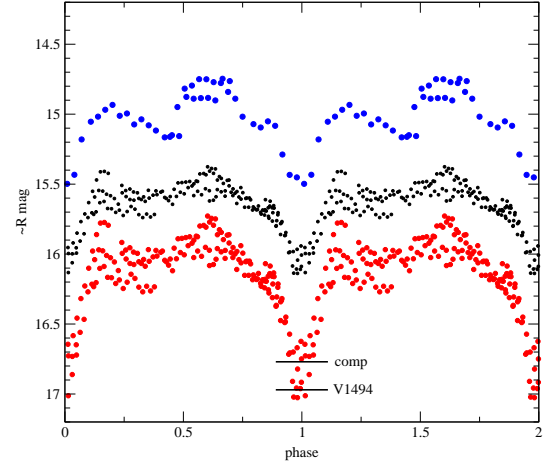|	nova	companion
RA(2000)	$19^h23^m05\overset{s}{.}37$	$19^h23^m05\overset{s}{.}29$
D(2000)	$04°57'19\overset{''}{.}79$	$04°57'18\overset{''}{.}85$
R ($\phi = 0.035$)	$16\overset{m}{.}98$	$16\overset{m}{.}78$
I ($\phi = 0.002$)	$16\overset{m}{.}32$	$15\overset{m}{.}80$

Fig. 3. Eclipsing light curves. Upper curve: integrated magnitudes calculated from the flux-calibrated AAT spectra; middle curve: phase diagram of all data taken in August, 2003; lower curve: the same after correcting for the secondary light.

We have two conclusions based on Fig. 2. Firstly, the positional agreement between the eclipsing star and the nova coordinate measured by D. di Cicco (Pereira et al. 1999) shows the nova and the eclipsing binary do indeed coincide. Secondly, the pre-outburst USNO position falls almost exactly halfway between the nova and the companion. We interpret this as an indirect evidence of the similar apparent brightnesses for the progenitor and the companion.

3.2. Photometry

It is evident from Fig. 1 that the nova has been fainter than the companion both in R and I (by chance, the analysed images were taken very close to the primary eclipse, the ephemeris in Kato et al. 2003 gives $\phi(R) = 0.035$ and $\phi(I) = 0.002$). This means the estimated contribution of the companion is much larger than quoted in Barsukova & Goranskii (2003) ($\sim$34% in R) and it may present a significant problem when modelling the light curve. To quantify it, we have measured relative magnitudes in respect to GSC 0473–4227 ($R = 12\overset{m}{.}94$, $I = 12\overset{m}{.}05$, Barsukova & Goranskii 2003) and corrected the light curve accordingly. Neglecting colour-dependent transformation terms (being in the order of a few hundredth mag for a wide range of colour differences, Sung & Bessell 2000), the resulting magnitudes (Table 1) revealed that the nova was fainter by $0\overset{m}{.}20$ in R and by $0\overset{m}{.}52$ in I. The error budget of these values consists of the individual psf-fitting errors calculated by the task *allstar* ($0\overset{m}{.}05$ for the nova and the companion and $0\overset{m}{.}006$ for the comparison), the uncertainty of the standard magnitudes of the comparison ($0\overset{m}{.}02$) and the neglected colour transformation terms (we assumed $0\overset{m}{.}02$). Consequently, the final uncertainty is about $0\overset{m}{.}06$ (it is marginally better in I thanks to the better resolution).

We illustrate the secondary light correction in Fig. 3 (the companion's magnitude was transformed to flux and was subtracted from the flux values of the light curve data; the results

were transformed back to magnitudes). The middle curve in Fig. 3 shows the phased R-band data (using the ephemeris in Kato et al. 2003: $BJD_{min} = 2\,452\,458.3230 + 0.1346138 \times E$), while the corrected curve is the bottom one. The eclipse depth (defined as the brightness difference between $\phi = 0$ and $\phi = 0.15$) has increased by a factor of two from $\sim 0\overset{m}{.}6$ to $\sim 1\overset{m}{.}2$, which is obviously not a negligible effect. It is quite surprising that none of the recent studies applied this correction. On one hand, both Barsukova & Goranskii (2003) and Pavlenko et al. (2003) mentioned the presence of the companion but they did not go beyond that. On the other hand, despite using unfiltered observations heavily influenced by the red companion, Kato et al. (2003) did not even mention the problem. Our conclusion is that one has to be very careful when analysing observations of V1494 Aql and reliable modelling requires accurate correction to the light of the companion.

3.3. Spectroscopy

Further details on the companion's nature are provided by the AAT spectroscopy. A sample spectrum is shown in the upper panel of Fig. 4. Beside a flat continuum, the spectrum is dominated by the complex Hα line and an emission blend at 6080 Å. Weak absorption lines are present in the blue and the red third of the spectrum, of which the red one mostly contains atmospheric telluric lines. In the blue part the sodium D is the strongest absorption. The integrated fluxes converted to mag-
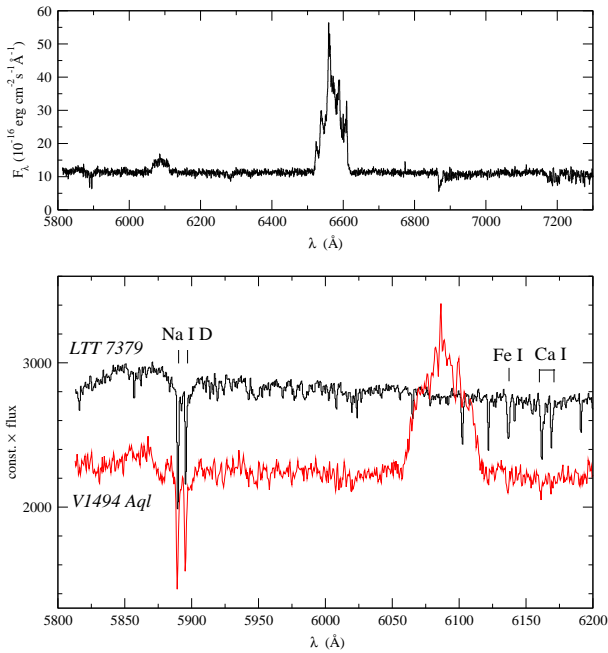
Fig. 4. Top panel: a sample AAT-spectrum of V1494 Aql. Note the symmetric structure of the Hα profile. Bottom panel: a close-up view of the bluest quarter compared to the flux-standard.

nitudes draw the same eclipsing light curve as the CCD observations do (see the top curve in Fig. 3). After recognizing the problems with the companion, we checked the original spectrum images and found that nova spectra were indeed wider than the standard ones (but not wide enough for deblending). That means we had the same contamination from the companion as in the case of the imaging.

The absence of molecular bands in the spectrum exclude the possibility of a late-type companion. Furthermore, we could identify a number of common absorption lines in the spectra of the nova and the G0-type flux standard. The most prominent ones are marked in the bottom panel of Fig. 4. The resemblance suggests the spectral type of the companion is similar to the flux standard, most likely between late F and early G.

Finally, the sodium D line has some interesting properties. Iijama & Esenoglu (2003) detected strong interstellar sodium D lines three months after the outburst. They measured the following equivalent widths: $EW_{D1} = 0.46 \pm 0.01$ Å and $EW_{D2} = 0.55 \pm 0.01$ Å. As a comparison, the blended AAT spectra result in $EW_{D1} = 0.50 \pm 0.02$ Å and $EW_{D2} = 0.65 \pm 0.02$ Å, with possible greater systematic uncertainty due to the ambiguous continuum level. The larger equivalent widths are consistent with the assumption that we see a sum of stellar and interstellar absorptions. Since we do not detect any additional line doubling of the doublet (within ± 5 km s^{-1}), either the $\sim$G-type companion has similar radial velocity than the cloud in which the interstellar component, detected by Iijama & Esenoglu (2003), originated or the continuum we see in Fig. 4 mostly comes from the reddened companion (in which case the radial velocities of

the companion and the cloud still have to agree unless the cloud is farther away).

4. Conclusions

V1494 Aql is an intriguing eclipsing nova that has initiated recently a number of independent photometric and spectroscopic studies. Judged from the publications, none of them has tried to correct for the effects of the close companion. With the presented properties of the star, this neglect can be dangerous and has the potential to lead to unreliable light curve models. The red and far red spectral regions are especially affected by the companion, which is a major obstacle to using unfiltered CCD measurements.

Based on the results presented in this paper, we can summarize our knowledge on the companion of V1494 Aql. It is located 1″.4 SW of the eclipsing nova. In minimum, the nova is fainter by 0.$^{\rm m}$2 in R and 0.$^{\rm m}$52 in I, while in maximum, it is brighter by about 0.$^{\rm m}$6–0.$^{\rm m}$8 in R, depending on the highly variable light curve shape (see Pavlenko et al. 2003 and the scatter of the phase diagrams in Fig. 3). A tentative spectral type has been assigned to the companion based on medium-resolution spectra with the AAT.

Adopting $E(B - V) = 0.^{\rm m}6$, $d = 1.6$ kpc and assuming the mean corrected R magnitude ($\sim 16.^{\rm m}3$) of the nova is close to the quiescent brightness, the progenitor's absolute magnitude was about $M_{\rm R} = 3.^{\rm m}9$, which leaves unchanged our conclusion on it (Kiss & Thomson 2000). However, further high-resolution imaging, preferably made under sub-arcsecond seeing, is needed in order to allow accurate photometric corrections and light curve modelling.

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